

account in specifying the methods to be used in the melt circulation steelmaking loops for continuous steelmaking without disruptive ebullition and ejection of melt from bubbles as they burst through the flowing melt surface with consequential skull or accretion build-up on the walls and roof of the reactor, which would eventually necessitate shutdown of the continuous steelmaking plant. In the present invention, this is secured by adapting the processing conditions so that the supply of carbon to the melt surface by liquid phase mass transfer throughout all of the steelmaking loops is always adequate to prevent oxygen atoms from diffusing into the molten metal to such an extent that concentrations of both oxygen and carbon in the bulk molten iron reach supersaturation levels sufficient to induce the decarburisation reaction to occur spontaneously beneath the surface.

For the particular case of coal-based continuous steelmaking, two steelmaking loops are preferred. The first is top blown to effect primary decarburisation, whilst in the second loop what has been termed “open-channel” decarburisation is promoted under increased melt circulation rate. For both loops, steady-state conditions are established such that gas phase mass transfer, interfacial chemical kinetics and liquid phase mass transfer all balance each other.

BRIEF DESCRIPTION OF THE DRAWINGS

Particular examples of the invention as applied to direct coal-based continuous steelmaking will now be described with reference to the accompanying drawings in which:-

Fig. 1 is a schematic general arrangement in plan view of the plant for direct coal-based continuous steelmaking, when steel scrap, hot briquetted iron (HBI), or direct reduced iron (DRI) are readily available and their use is economical.

Fig. 2 is a schematic general arrangement in plan view for direct coal-based continuous steelmaking for a stand-alone plant based on virgin ore as the only source of iron units.

Referring now to Fig. 1, the plant comprises six furnace hearths 1, 2, 3, 4, 5 and 6, which are arranged in pairs to form three inter-linked melt circulation loops A (a charge reduction loop), B and C (first and second refining loops) formed by interconnecting the first and

second hearths 1 and 2 (constituting a charge reduction and a desulphurisation/heating zone respectively), the third and fourth hearths 3 and 4 (constituting a melting zone and a desulphurisation/decarburisation zone) and the fifth and sixth hearths 5 and 6 respectively. Under steady operating conditions, molten metal is caused to overflow or be otherwise taken out of the second and third loops B and C by conductively heated siphons 7 and 8 so that molten metal issuing from these is equivalent to the metal in the composite charge initially added to the top surface of the molten carrier material at the upstream end of the first hearth 1, together with any scrap or pre-reduced material added to the circuit and shown in Fig. 1 as 12. At the downstream end of the first hearth 1, a channel or ramp 8 is provided to permit solid material (metallised raft) floating on the surface of the molten carrier material in the first hearth 1 to be propelled or projected into the third hearth 3 onto the surface of the molten carrier material in the first refining loop B, along with a lesser amount of molten carrier material from the reduction loop A, corresponding to new metal assimilated into the carrier material in reduction loop A, resulting from any smelting reduction taking place between the floating charge layer, ultimately becoming an agglomerated solid structure referred to as the metallised raft as it progresses downstream in the first hearth 1.

Forced melt circulation in all loops is effected by R-H type snorkels 9 connected to vertical bodies 10 linked to each other by horizontal members 11 to form vacuum-tight refractory-lined vessels, which can function either as gas-lift pumps or siphons depending on whether or not an inert gas is injected into the upleg snorkels. Under reduced pressure melt is drawn up into both snorkels 9 and the lower regions of the vertical bodies 10 and the horizontal members 11 in each unit to form a channel through which the melt traverses as it flows from one hearth to another along the horizontal member 11. These vessels can be either lowered so that the snorkels 9 are immersed in the molten carrier materials or raised for stand-by or replacement with preheated units on a scheduled maintenance basis.

The very much smaller siphons 7 and 8 have similar features to the units described above, but because the melt flow rates in these siphons correspond to the actual metal production rate, steps may need to be taken to independently heat the flowing metal by direct resistance heating or so-called conductive heating.

The composite charge 12, comprised of well-mixed iron ore fines, fine coal and preferably burnt lime flux, is distributed uniformly onto the surface of the molten carrier material towards the upstream end of the first hearth 1 to form a floating charge layer 5 to 10 cm in thickness, whilst being heated from beneath by the molten carrier material. Coal volatiles and reaction product gases are discharged from the gas space above the floating solid charge into a refractory-lined gas header duct 13, which forms the manifold for an array of top blowing lances with concentric controlled oxygen admission so that the metallised raft floating in the third hearth 3 is melted to form a liquid slag layer, whilst the metallics are assimilated into the molten carrier material. Slag is removed at the downstream end of the third hearth 14 either continuously or intermittently from a pool of molten slag formed when the molten metal is held back by an electromagnetic device or dam similar to that being developed for continuous casting applications.

The gases flow from the third hearth 3 into a hot gas clean-up (HGCU) facility, which incorporates a combined liquid-metal quench and desulphurisation tower 15, a turbo-booster 16 and a liquid-metal based gas reheater 17. In other embodiments (not shown), the gases are arranged to flow into the HGCU facility from the first hearth.

With its pressure now increased, the hot gas from the HCGU flows into a refractory-lined header duct 18, which forms the manifold for an array of top blowing lances with further controlled concentric oxygen addition so that carbon dioxide and water vapour become the oxidant gases rather than oxygen itself for primary or major decarburisation of the molten carrier metal in the fourth hearth 4 using direct flame impingement to provide both the thermal requirements and the gaseous reactant for the endothermic decarburisation reaction.

Besides providing the principal decarburisation requirements, the fourth hearth 4 is used to effect flux-based desulphurisation, whilst the dissolved oxygen content of the iron is relatively low and the carbon level sufficiently high to sustain this requirement. Accordingly, desulphurisation flux is added at the upstream end of the fourth hearth 19 and removed at its downstream end 20.

The hot gases from the fourth hearth 4 discharge into a refractory-lined header duct, which forms the manifold for an array of top blowing lances 21 with further concentric controlled oxygen addition to effect melting of preheated steel scrap or prereduced material in a pool of molten metal 22, which overflows liquid scrap into the fifth hearth 5 where the melt is flowing at an accelerated rate in the end in which open-channel decarburisation of the melt siphoned from the fourth hearth 4 is effected by contacting the melt in the fifth hearth 5 with the oxidising gases leaving the pool melter 22 under turbulent flow conditions.

Because of the lesser amount of decarburisation that occurs in the second refining loop C, the sensible heat of the gases leaving the pool melter 22 is more than adequate to provide the endothermic requirements of secondary decarburisation before the gas flows into the sixth hearth 6 via the refractory-lined cross-over gas duct 23. Because the carbon level throughout the second refining loop C is low, the melt is effectively steel for general purpose applications and the dissolved oxygen level is high enough to conduct flux-based deposphorisation by adding powdered flux at the upstream end 24 of the sixth hearth and removing flux at the downstream end 25.

After passing along the length of the sixth hearth 6, the hot gases discharge into a refractory-lined transfer duct 26, which becomes the manifold 27 for an array of top blowing lances with major concentric oxygen addition (or other suitable configuration such as mutually opposed jets) to effect combustion to completion of the gases emitted initially from the reduction loop A via the off-take 13 into the first of the refining (steelmaking) loops B. This major combustion utilises direct flame impingement onto the molten carrier material in the second hearth 2 to contribute towards the post combustion energy needed to sustain ironmaking in the first hearth 1.

A small amount of a desulphurisation flux, which wets the melt surface and spreads across it to form a continuous thin film on the surface of the molten carrier material, is added at the upstream end 28 of the second hearth 2 and taken away at its downstream end 29. This contributes to desulphurisation in the circuit, but most importantly raises the emissivity of the molten carrier material and so considerably enhances heat transfer by radiation. The very hot combustion gases are discharged into a refractory-lined off-take 30, possibly with stave cooling within the refractory lining, directly into a countercurrent radiant scrap preheater 31, in which a sloping hearth plus a mechanical device is used to

contact selected steel scrap 39 to effect major scrap preheating and possible partial melting, before the scrap or other reduced material passes into the pool melter 22. The off-gas from the scrap preheater leaves the plant at 32 and can be used in a heat recovery steam generator (HRSG) for advanced power generation.

Vacuum degassing of steel using the RH process is established practice throughout the world. By injecting argon into a single upleg, molten steel circulation at rates up to about 200 tonne per minute can be obtained and this is now regarded as state of the art in the steel industry. However, elaborate vacuum plant as used in RH degassing is not needed for the melt circulation systems in the present invention. Argon can be used as the lift gas but it may be preferable to use the desulphurised gas arising from ironmaking whilst it is still not oxidising iron, because argon is needed elsewhere in the circuit, particularly if ultra-low carbon steel (ULC) is to be produced continuously using the molten steel discharging from 8 as the feed into the Tower Refiner described previously.

It must be stressed that the overall energy implications of melt circulations as shown schematically in Fig. 1 are minimal. To circulate melt through a closed loop path is a function of the product of the rate at which melt is circulated times the total liquid head to be pumped against. For the present case, differences in level throughout the whole system are mainly due to frictional effects and other phenomena associated with open channel fluid flow at high throughput. Accordingly, the pumping heads can be kept small by design so that very large circulation rates can be employed for the various molten carrier materials without consuming undue amounts of energy.

For the steel industry world-wide, the ultimate vision is perpetual recyclability with steel scrap being recycled again and again with input from iron ore only utilized to accommodate growth in demand. This embodies the desirable concept of environmental sustainability, requiring conservation of natural resources (iron ore and coal), minimizing the production of CO₂ in the first instance and sequestration of whatever CO₂ is produced to combat climate change and global warming.

To maximize scrap melting or charging of DRI, HBI etc. if so desired, all of the gases emitted from the ironmaking loop A need to be utilized together in both of the steelmaking loops B

and C. Ideally, the smelting reduction gases in total need to be passed directly to the metallised raft melting arm (hearth 3) of the primary steelmaking loop A and partially combusted with oxygen with direct flame impingement using an array of top blow lances to effect iron melting and liquid slag formation as the metallised raft floats along with the circulating iron carbon melt with phase disengagement completed when a molten slag layer free from associated iron is established towards the downstream end of the arm in question, in advance of slag removal from the circuit.

To ensure high iron recovery, metallic iron is maintained as the thermodynamically stable phase by controlling the oxygen addition in both the smelting reduction arm (hearth 1) of the ironmaking loop A and the metallised raft melting arm (hearth 3) of the primary steelmaking loop B.

The principal supply of heat for smelting reduction is by melt circulation in the ironmaking loop A. Soot formation as coal is devolatilised and reduction commenced is precluded by minor oxygen admission above the charge material as it floats down the charge arm (hearth 1) of the ironmaking loop A but the mixed gases are never allowed to become oxidizing to metallic iron, either here or after the flame impingement top blow arrangement for melting the metallised raft in the first steelmaking loop B. This is a unique feature, only feasible in a melt circulation system, and guarantees very high iron recovery without oxidation losses. It assumes, of course, that the retention time in the ironmaking arm (hearth 1) is adequate to achieve a high degree of metallisation in the first instance. Once solid metallic iron is formed it will be impossible to lose any of this by solution in the slag, nor can it be oxidized within the ironmaking furnace itself.

Direct flame impingement was selected so that metallic iron at unit activity can be melted directly without relying on dissolution in the Fe-C melt. Similarly, the processes involved in slag formation are accelerated by this approach.

Very little of the heat required in the steelmaking loops is derived from the sensible heat of the circulating melt. This has important implications relating to the design of the above bath enclosures. Low thermal mass insulating materials, commercially available, are incorporated throughout the walls and roofs of both steelmaking loops A and B and for the charge side

(hearth 1) of the ironmaking loop A. It is only the desulphurisation/heating arm (hearth 2) of the ironmaking loop A which may require a high specification refractory enclosure, although even here it may be feasible to use low thermal mass and relatively inexpensive insulating materials currently being developed. Obviously this must have a major impact in terms of capital cost savings. It also facilitates easy access to the hearths, if needed, and generally reduces the structural requirements because the materials involved are lightweight in comparison with brickwork or castable refractories.

The hot gases undergo hot gas cleanup (HGCU) involving a liquid metal quench, which incorporates sulphur removal to a very high level as well as removal of particulate solids, before being boosted in pressure to around 0.5 to 1 bar gauge and reheating again by liquid metal direct heat exchange. The gases are returned to the steelmaking loop B at about 1350°C for partial combustion with oxygen to provide the chemical and thermal requirements for major decarburisation of Fe-C melt by direct flame impingement under non-splashing top blow conditions on the desulphurisation flux arm (hearth 3) of the primary steelmaking loop B. The momentum of the jets clears the flux away and mixes it to assist desulphurisation, whilst promoting liquid phase mass transfer of dissolved carbon from the bulk of the liquid metal to the interface, where the endothermic reactions with CO₂ and H₂O take place.

The top blow lances are designed so that the supply of gaseous oxidant to the liquid metal interface at steady state is balanced by the supply of carbon by liquid phase mass transfer. Allowance is also made for the kinetics of the dissociative adsorption of both CO₂ and H₂O, including the inhibiting effects of sulphur. The resulting steady state conditions are such that sub-surface CO bubble formation cannot take place. Laboratory experiments using the electromagnetic levitation technique have established that sparking or copious fume generation will not occur under these relatively mild conditions.

The gases during decarburisation may gain enough CO by reaction that they may leave the primary steelmaking loop A with metallic iron again as the stable thermodynamic phase. Further controlled addition of oxygen is made to these gases in another top-blow flame impingement arrangement, this time directed at a pool of molten iron, which is essentially a cul-de-sac off the second refining loop C for what is termed open-channel decarburisation. This pool receives partially melted steel scrap from a radiant heater in the form of a sloping

hearth, leading directly into the pool and fired by the very hot gases from the second hearth. The overflow from the pool is liquid scrap, which joins the main melt circulation flow, any non-metallic residues being incorporated into the dephosphorisation flux layer as it floats down this arm (hearth 5) of the open-channel decarburisation loop C. The hot gas mixture then transverses the length of the open-channel decarburisation arm (hearth 5), where a clean metal surface permits further decarburisation to a low level without sparking or fume emission and then the hot gases are ducted to the heating arm 2 of the ironmaking loop A where further oxygen is added for full combustion before exiting to the sloping hearth radiant heater for partial melting of steel scrap at a temperature at between 1700-1800°C at the inlet with countercurrent contacting of the incoming scrap feed.

The gases ultimately leave the radiant heater at around 850°C for transmission to the heat recovery steam generator (HRSG), which together with the steam tubes associated with the various frozen shells constitute the steam boiler for advanced power generation.

The embodiment described above when applied to plant for continuously producing steel from iron ore fines, when steel scrap, HBI or DRI are both readily available and economic to use, would typically produce three tonnes of steel product from every one tonne of virgin iron units incorporated into the composite mixed feed.

There will always, of course, be a need for creation of value-added products by primary production away from centres of high population and scrap availability and, ideally, new technology must be able to switch easily from high scrap utilisation to 100 pct virgin raw materials, if the situation so demands. It is this in-built flexibility that is a key feature of the present invention. In place of the scrap melting arrangement shown in Fig. 1, the gases in 21 flow directly to the fifth hearth 5, the pool melter 22 and the radiant scrap preheater are both eliminated.

This means that extra combustion is available in the second hearth and to prevent this from over heating it is necessary not to fully combust the gases therein but to pass the very hot gases now containing residual CO and H₂ directly to a Waste Heat Boiler (WHB), probably with CO₂ recirculation to moderate temperatures. In the event, more electricity than needed for air separation and CO₂ liquefaction will be generated. Depending on the proximity of

other plant nearby or other in-plant usage, some of the power generated would be available for export to the grid if such an opportunity exists in centres away from densely populated areas. Alternatively, if steel scrap is not readily available and the use of HBI or DRI is uneconomic, this becomes the preferred option with export of electricity to the national grid.

Referring now to Fig. 2, a stand-alone plant retains the principal features of having six furnace hearths, which are arranged in pairs to form three inter-linked melt circulation loops. Except for the changes discussed above in relation to the non-availability of steel scrap at the right price and assuming that using HBI or DRI is also not economic, the other features in Fig. 2 are essentially the same as those shown in Fig. 1 and corresponding reference numerals are used accordingly. For the stand-alone plant, however, since excess thermal energy is available, it may be desirable to incorporate calcination of limestone 33 to burnt lime 34 into the circuit. This is shown schematically in Fig. 2 as an adjunct downstream of the off-take 30 of the very hot gases from the post combustion arm (hearth 2) of the ironmaking loop A. It involves recycling a stream 35 of CO₂ and H₂O at a temperature at around 125°C from the exit flue of the WHB to attemperate the gas leaving hearth 2 through the off-take 30, which is split into two streams, into one of which powdered limestone 33 is injected. Sufficient residence time is provided in the gas flow path within the calciner 36 to produce burnt lime 34, which is recovered by a cyclone separator 37 and the combined gases 38 then proceed to the WHB. This burnt lime is one of the principal components of the mixed composite charge 12 and may also be used in preparation of the desulphurisation flux 19 and the dephosphorisation flux 24.

The method according to the present invention is not solely applicable to iron oxide ores such as haematite, but is also applicable for example, to the production of refined metal or alloy from the following:

- (1) Chrome ores to form ferrochromium alloys.
- (2) Chromite together with nickel sulphide to make master alloys for stainless steelmaking.
- (3) Chromite and nickel oxide for direct stainless steelmaking.
- (4) Nickel laterites to form ferronickel directly.
- (5) Deepsea manganese nodules to form copper-nickel-iron alloy (furnace alloy).
- (6) Manganese ore to ferromanganese alloys.